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Observed and physical properties of type II plateau supernovae

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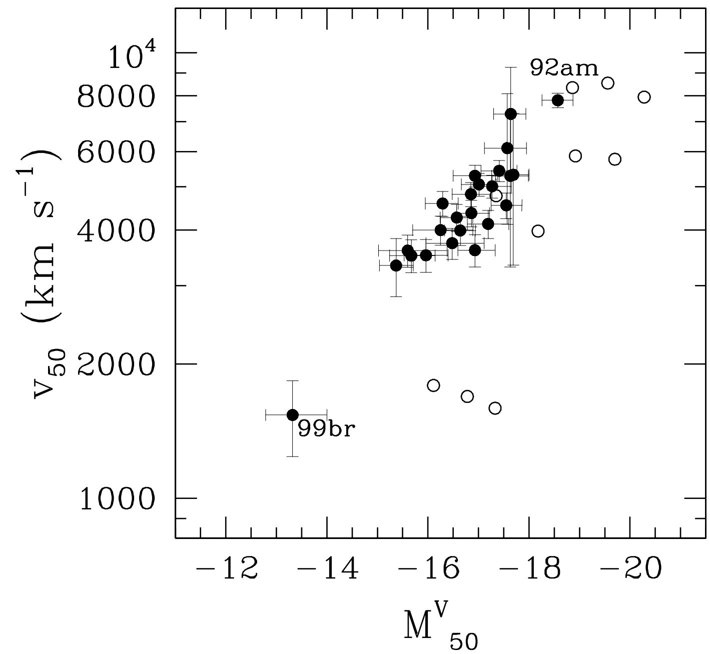
1.1 Introduction

Type II supernovae (SNe II, hereafter) are exploding stars characterized by strong hydrogen spectral lines and their proximity to star forming regions, presumably resulting from the gravitational collapse of the cores of massive stars (M_{ZAMS}>8 $M_\odot$). SNe II display great variations in their spectra and lightcurves depending on the properties of their progenitors at the time of core collapse and the density of the medium in which they explode. Nearly 50% of all SNe II belong to the plateau subclass (SNe IIP) which constitutes a well-defined family distinguished by 1) a characteristic "plateau" lightcurve (Barbon et al. 1979), 2) Balmer lines exhibiting broad P-Cygni profiles, and 3) low radio emission (Weiler et al. 2002). These SNe are thought to have red supergiant progenitors that do not experience significant mass loss and are able to retain most of their H-rich envelopes before explosion. In section 1.2 I summarize the observed properties of SNe IIP based on a sample of 24 objects, and in section 1.3 I use published models to derived physical parameters for a subset of 13 SNe.



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1.2 Observed properties of Type II plateau supernovae

In Hamuy (2003; H03 hereafter) I compiled photometric and spectroscopic data from my own work and a variety of publications, for a sample of 24 SNe II. In Table 2 of that paper I summarized observed parameters, such as the absolute V magnitude near the middle of the plateau (M^V_{50}), the duration of the plateau, the velocity of the expanding envelope measured near the middle of the plateau (v_{50}), and the luminosity of the exponential tail (converted into ^{56}Ni mass ejected in the explosion). The wide range in luminosities and expansion velocities is clear manifestation of the great diversity of SNe IIP.

Figure 1.1 shows that, despite this diversity, the SN plateau luminosities

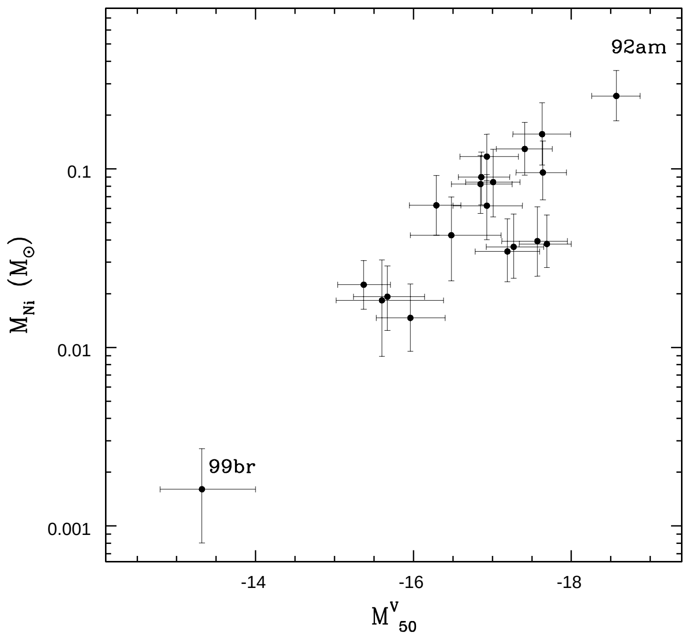

Fig. 1.2. Mass of ^{56}Ni ejected versus plateau luminosity measured 50 days after explosion.

are well correlated with the expansion velocities. Also shown with open circles are the explosion models of Litvinova & Nadezhin (1983, 1985, hereafter LN83 and LN85) for stars with $M_{ZAMS} \geq 8\ M_{\odot}$. It is clear that the luminosity-velocity relation is also present in the theoretical calculations. This comparison suggests that one of the main parameters behind this diversity is the explosion energy, which causes great variation in the kinetic and internal energies. A similar result was recently found by Zampieri et al. (2003b).

In figure 1.2 I compare the luminosity during the plateau and exponential phases. The latter is expressed in terms of the mass of ^{56}Ni ejected, M_{Ni}, assuming that the late-time lightcurve is powered by the full trapping and thermalization of the γ rays due to ^{56}Co $\rightarrow$ ^{56}Fe (^{56}Co is the daughter of ^{56}Ni, which has a half life of only 6.1 days). There is clear evidence that SNe with brighter plateaus also have brighter tails. A similar result was recently

found by Elmhamdi et al. (2003). Note that this correlation is independent of the distance and reddening adopted for each SN.

The previous analysis shows that several regularities emerge among the observed properties of SNe IIP. Within the current uncertainties a single parameter is required to explain the variations in luminosity and expansion velocity.

1.3 Physical properties of Type II plateau supernovae

Using hydrodynamic models, LN83 and LN85 derived approximate relations that connect the explosion energy (E), the mass of the envelope (M), and the progenitor radius (R_0) to three observable quantities, namely, the duration of the plateau, the absolute V magnitude, and the photospheric velocity observed in the middle of the plateau. These formula provide a simple and quick method to derive E, M, and R_0 from observations of SNe II-P, without having to craft specific models for each SN.

Of the 24 SNe II-P considered above only 13 have sufficient data to apply the method of LN85. The light curves for these SNe are shown in Fig. 1.3. The input parameters are listed in Table 3 of H03 and the output parameters are summarized in Table 1.1. This table includes physical parameters for 3 additional SNe available in the literature, namely, SN 1987A (Arnett 1996), SN 1997D and SN 1999br (Zampieri et al. 2003a). Although SN 1987A showed an atypical lightcurve due to the compact nature of its blue supergiant progenitor, it was not fundamentally different than ordinary SNe II-P in the sense that it had a hydrogen-rich envelope at the time of explosion. For this reason I include it in this analysis. To my knowledge these are the only 16 SNe IIP with available physical parameters.

Among this sample, 9 SNe have explosion energies close to the canonical 1 foe value (1 foe=10^{51} ergs), 6 objects exceed 2 foes, and one has only 0.6 foes. SN 1992am and SN 1999br show the highest and lowest energies with 5.5 and 0.6 foes, respectively. This reveals that SNe II encompass a wide range in explosion energies. The ejected masses vary between 14 and 56 $M_\odot$. Although the uncertainties are large it is interesting to note that, while stars born with more than 8 $M_\odot$ can in principle undergo core collapse, they do not show up as SNe II-P. Perhaps they undergo significant mass loss before explosion and are observed as SNe IIn or SNe Ib/c. It proves interesting also that stars as massive as 50 $M_\odot$ seem able to retain a significant fraction of their H envelope and explode as SNe II. Objects with M>35 $M_\odot$ are supposed to lose their H envelope due to strong winds, and become Wolf-Rayet stars before exploding (Woosley et al. 1993). This result suggests

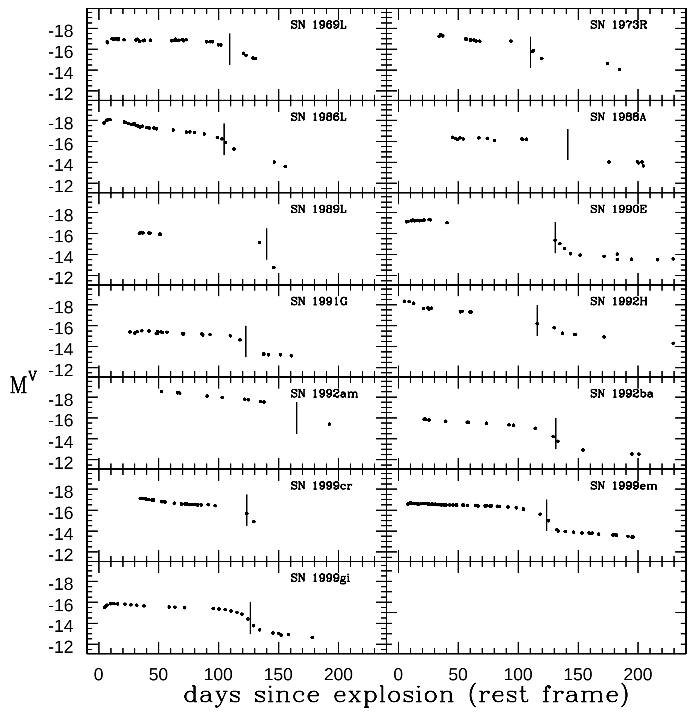

Fig. 1.3. Extinction corrected absolute V-band lightcurves of the 13 SNe IIP. The vertical bars indicate the end of the plateau phase for each supernova.

that stellar winds in massive stars are not so strong as previously thought, perhaps due to smaller metallicities. Except for four objects, the initial radii vary between 114 and 586 $R_\odot$. Within the error bars these values correspond to those measured for K and M red supergiants (van Belle et al. 1999), which lends support to the generally accepted view that the progenitors of SNe II-P have extended atmospheres at the time of explosion (Arnett 1996). Three of the SNe II-P of this sample, however, have $R_0 \sim 80\ R_\odot$ which corresponds to that of G supergiants. This is somewhat odd because in theory such objects cannot have plateau lightcurves but, instead, one like that of SN 1987A. Note, however, that the uncertainties are quite large and it is possible that these objects did explode as red supergiants.

Figure 1.4 shows M and M_{Ni} as a function of E for the 16 SNe II-P. Despite the large error bars, this figure reveals that a couple of correlations emerge from this analysis. The first interesting result (top panel) is that the explosion energy appears to be correlated with the envelope mass, in

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SN	Energy (10^{51} ergs)	Ejected Mass ($M_\odot$)	Initial Radius ($R_\odot$)	References
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1986L	$1.3^{+0.5}_{-0.3}$	17^{+7}_{-5}	417^{+304}_{-193}	1
1987A	1.7	15	42.8	2
1988A	$2.2^{+1.7}_{-1.2}$	50^{+46}_{-30}	138^{+80}_{-42}	1
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1990E	$3.4^{+1.3}_{-1.0}$	48^{+22}_{-15}	162^{+148}_{-78}	1
1991G	$1.3^{+0.9}_{-0.6}$	41^{+19}_{-16}	70^{+73}_{-31}	1
1992H	$3.1^{+1.3}_{-1.0}$	32^{+16}_{-11}	261^{+177}_{-103}	1
1992am	$5.5^{+3.0}_{-2.1}$	56^{+40}_{-24}	586^{+341}_{-212}	1
1992ba	$1.3^{+0.5}_{-0.4}$	42^{+17}_{-13}	96^{+100}_{-45}	1
1997D	0.9	17	128.6	3
1999br	0.6	14	114.3	3
1999cr	$1.9^{+0.8}_{-0.6}$	32^{+14}_{-12}	224^{+136}_{-81}	1
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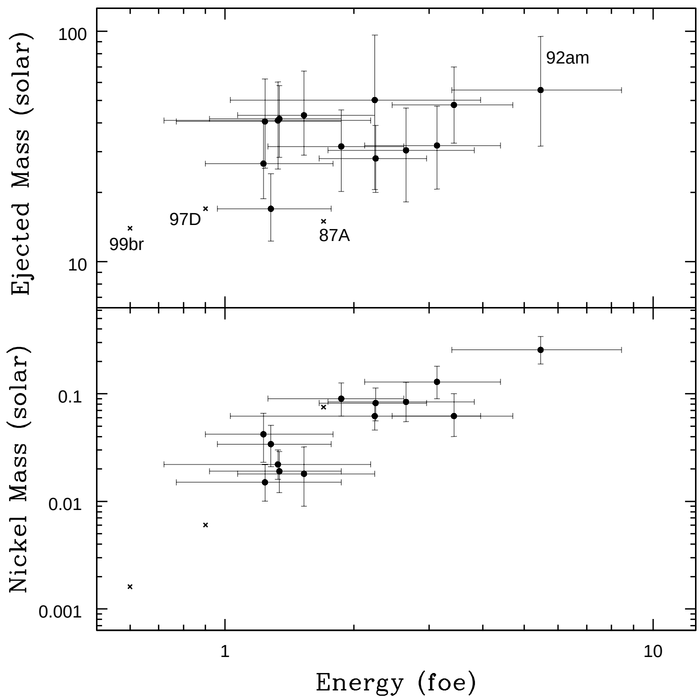
the sense that more massive progenitors produce more energetic SNe. This suggests that stellar mass plays a central role in the physics of core collapse. The second remarkable result (bottom panel) is that SNe with greater energies produce more nickel (a result previously suggested by Blanton et al. 1995). This could mean that greater temperatures and more nuclear burning are reached in such SNe, and/or that less mass falls back onto the neutron star/black hole in more energetic explosions.

1.4 Conclusions

1) SNe II-P encompass a wide range of ∼5 mag in plateau luminosities, a five-fold range in expansion velocities, and a 100-fold range in tail luminosities.
2) Despite this great diversity, SNe II-P show several regularities such as correlations between plateau luminosities, expansion velocities, and tail luminosities, which suggests a one parameter family, at least to first order.
3) There is a continuum in the properties of SNe II-P from faint, low-velocity, nickel-poor events such as SN 1997D and SN 1999br, and bright, high-velocity, nickel-rich objects like SN 1992am.
4) SNe IIP encompass a wide range in explosion energies (0.6-5.5 foes),



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ejected masses (14-56 $M_\odot$), initial radii (80-600 $R_\odot$), and ^{56}Ni yields (0.002-0.3 $M_\odot$).
5) Despite the large error bars, a couple of correlations emerge from the previous analysis: (1) more ^{56}Ni is ejected in SNe with greater energies; (2) progenitors with greater masses produce more energetic explosions. This suggests that the physics of the core collapse and the fate of massive stars is, to a large extent, determined by the mass of the progenitor.

Acknowledgements Support for this work was provided by NASA through Hubble Fellowship grant HST-HF-01139.01-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555.

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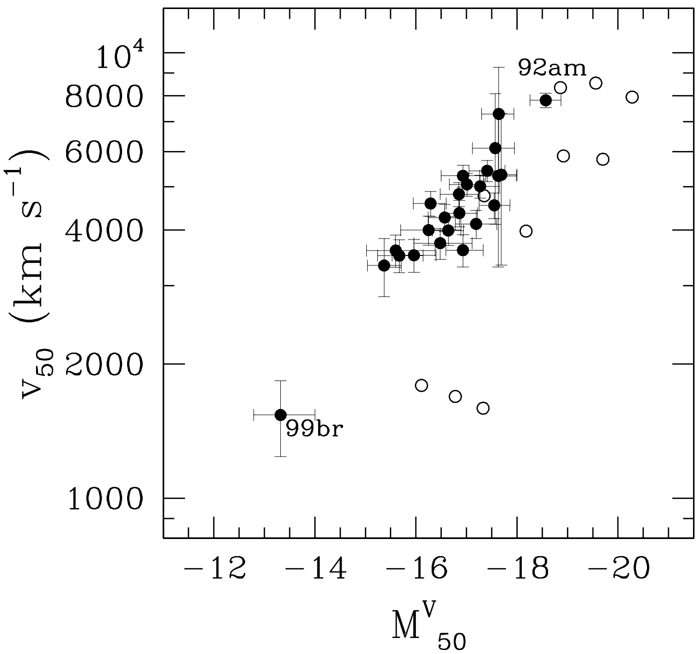

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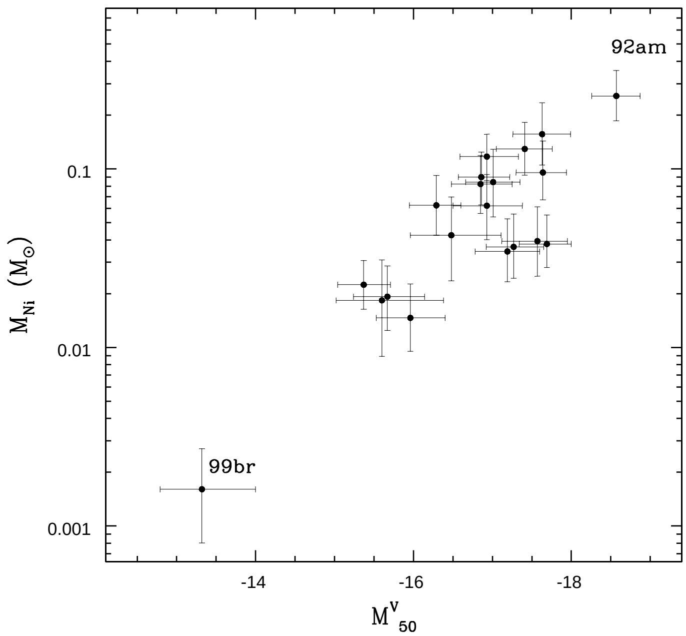

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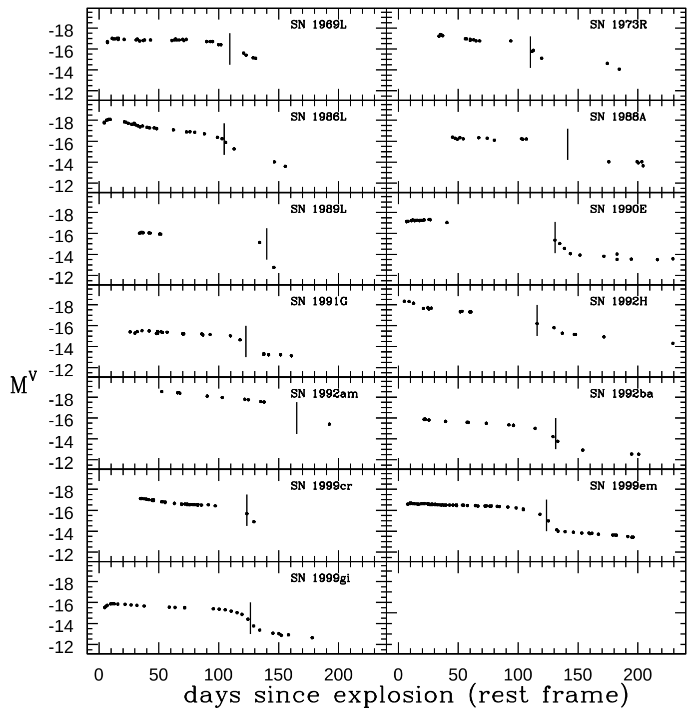

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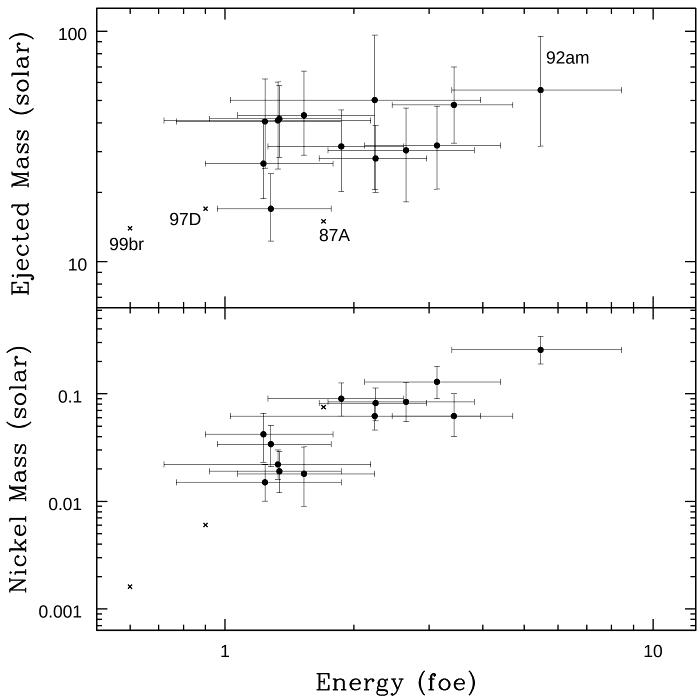

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